# In-Situ Resource Utilization (ISRU) for Human Exploration of the Moon & Mars

*Presentation to Lunar Strategic Roadmap Team*
*Jan. 24, 2005*

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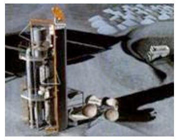
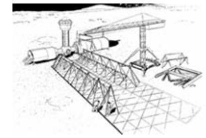
# *Uses of Space Resources for Robotic & Human Exploration*





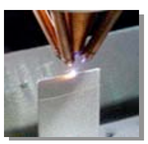

## Mission Consumable Production

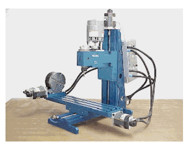
- **Propellants for Lander/Ascent Vehicles, Surface Hoppers, & Aerial Vehicles**
- **Fuel cell reagents for mobile** (rovers, EVA) & stationary backup power
- **Life support consumables** (oxygen, water, buffer gases)
- Gases for science equipment and drilling
- Bio-support products (soil, fertilizers, etc.)
- Feedstock for in-situ manufacturing & surface construction

## Surface Construction

- **Radiation shielding for habitat & nuclear reactors from in-situ resources or products** (Berms, bricks, & plates; water; hydrocarbons)
- **Landing pad clearance**, site preparation, roads, etc.
- Shielding from micro-meteoroid and landing/ascent plume debris
- Habitat and equipment protection






## Manufacturing w/ Space Resources

- **Spare parts manufacturing**
- Locally integrated systems & components (especially for increasing resource processing capabilities)
- High-mass, simple items (chairs, tables, chaises, etc.)




## Space Utilities & Power

- **Storage & distribution of mission consumables**
- Thermal energy storage & use
- Solar energy (PV, concentrators, rectennas)
- **Chemical energy (fuel cells, combustion, catalytic reactors, etc.)**

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# NASA Vision & Exploration Challenges

To Meet NASA's Mission and to meet the challenge "to explore the universe and search for life" robotic and human exploration must be **Sustainable, *Affordable*, Flexible, *Beneficial*,** and ***Safe***

| Strategic Challenges | How ISRU Meets Challenge |
|---|---|
| ***Margins & Redundancy*** | Use of common technologies/hardware and mission consumables enables swapping/cross use |
| | See ASARA |
| ***Reusability*** | Production of mission consumables (propellants, fuel cell reagents, science gases, etc.) enables reuse of typical single use assets |
| ***Modularity*** | ISRU utilizes common technologies/hardware with life support, fuel cell power, and propulsion systems |
| ***As Safe As Reasonably Achievable*** | Use of functional/dissimilar redundancy for mission critical systems (such as life support) increases mission safety |
| | ISRU can eliminate aborts which may occur without capabilities: life support, power, spare parts, etc. |
| | Use of in-situ materials for radiation shield enable lower levels of radiation exposure compared to Earth provided shielding |
| ***Robotic Networks*** | ISRU incorporates robotic networks to enable ISRU capabilities before human occupation |
| ***Affordable Logistics Pre-Positioning*** | ISRU enables large mass leveraging of pre-positioned hardware into usable mission products and consumables (space parts, propellants, life support gases, etc.) |
| ***Energy Rich Systems & Missions*** | Regeneration of fuel cell reagents and common mission consumables and hardware enables power-rich EVA suits, robotic assistants, and rovers without the cost/overhead associated with multiple nuclear assets (RTGs) |
| ***Access to Surface Targets*** | Production and regeneration of propellants and fuel cell reagents enables transport rovers and robotic and human surface hoppers at a fraction of the cost compared to dedicated missions launched from Earth |
| ***Space Resource Utilization*** | All of above |

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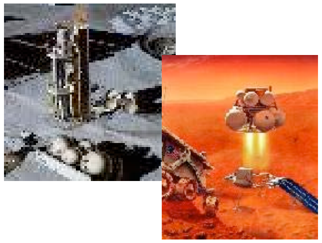
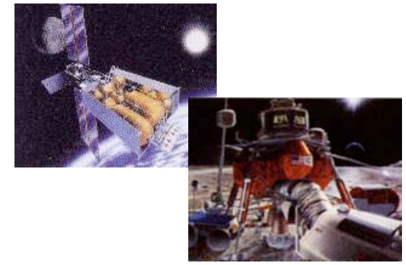
# *Space Resource Utilization is Critical for Affordable, Flexible, & Sustainable Exploration*



## Mass Reduction

- Reduces Earth to orbit mass by 20 to 45% for Mars missions
- 3.5:1 to 4:1 mass savings leverage from Moon/Mars surface back to Low Earth Orbit,



## Cost Reduction

- Reduces number and size of Earth launch vehicles
- Allows reuse of transportation assets
- Minimizes DDT&E cost

# Space Resource Utilization

## Risk Reduction & Flexibility

- Reduces dependence on Earth supplied logistics
- Use of common hardware & mission consumables enables increased flexibility
- In-situ fabrication of spare parts enables sustainability and self-sufficiency
- ISRU can provide dissimilar redundancy
- Radiation & Plume Shielding

## Expands Human Presence

- Increase Surface Mobility & extends missions
- Habitat & infrastructure construction
- Propellants, life support, power, etc.
- Substitutes sustainable infrastructure cargo for propellant & consumable mass

## Enables Space Commercialization

- Develops material handling and processing technologies
- Provides infrastructure to support space commercialization
- Propellant/consumable depots at Earth-Moon L1 & Surface for Human exploration & commercial activities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# ISRU Development & Incorporation Objectives

## Objectives of Lunar ISRU Development & Incorporation

- Identify and characterize resources on Moon, especially polar region
- Demonstrate concepts, technologies, & hardware that reduce the cost & risk of human Moon & Mars missions
- Use Moon for operational experience and mission validation for Mars
  - Pre-deployment & activation of ISRU assets
  - Making and transferring mission consumables
  - Landing crew with pre-positioned return vehicle or 'empty' tanks
- Develop and evolve ISRU to support sustained, economical human presence on Moon and use for Earth-Moon and L1-to-Mars transportation
  - Lower Earth-to-Orbit launch needs
  - Enables reuse of transportation assets and single stage lander/ascent vehicles
  - ➢ Lower cost to government by initiating *government-commercial* activities to enable space commercialization and by opening new markets

## Objectives of Mars ISRU Development & Incorporation

- Identify and characterize resources on Mars, especially water
- Demonstrate concepts, technologies, & hardware that reduce the cost & risk of human Mars missions
  - Lower Earth-to-Orbit launch needs
- Utilize Lunar demonstrated hardware & concepts to the maximum extent possible
- Enable human missions beyond Mars

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# Space Resource Utilization Dependencies

## Architecture Dependant:

- Long stay vs short stay *(mission consumable mass increases with stay time)*
- Pre-deploy vs all in one mission *(pre-deploy allows longer production times but requires precision landing)*
- Multiple mission to same destination vs single missions *(multiple missions enables gradual infrastructure and production rate build up)*
- High orbit vs low orbit rendezvous *(increase in Delta-V increases benefit of in-situ produced propellant)*
- Reuse vs single mission *(reuse allows for single stage vs two stage landers and lower cost propellant depots at E-M L1)*

## Customer dependant:

- ISRU is only viable if use is designed into subsystems that utilize the products *(propellants, radiation shielding, energy storage, surface equipment, spare parts, etc.)*

## Time phased:

- Early missions must require minimum infrastructure and provide the biggest mass/cost leverage *(mission consumables have biggest impact)*
- Surface construction and manufacturing will start with simple/high leverage products and expand to greater self-sufficiency capability
- ISRU is evolutionary and needs to build on lessons learned from previous work and show clear benefit metrics

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# Lunar ISRU Implementation Approach

## Lunar Mission Assumptions with ISRU (Lunar Exploration Analysis Group-LEAG)

- Robotic precursors to identify resources and validate critical processes
- Early human missions (4 to 14 days) to check out systems and operations until long-term candidate site selected
  - Pre-deployed ISRU/mission assets before human missions
- Develop infrastructure at one base for Mars mission 'dress rehearsals' (90 day & 500 day) and sustained human presence in space
  - Traverse or hop to other locations for short term science mission objectives

## Initial Capabilities

- Surface regolith excavation
  - Excavation for volatile extraction and regolith processing
  - Berms and shielding for radiation and plume protection
  - Site/landing pad preparation and road/dust mitigation
- Extraction & recovery of useful volatiles from surface resources ($H_2$, CO, $N_2$, $H_2O$)
- Oxygen ($O_2$) production from regolith processing
- Production/regeneration of fuel cell reagents
- Cryogenic storage & transfer

## Mid-Term ISRU Capabilities

- In-situ fabrication and repair
- Space Power
- Thermal energy storage & use

## Long-Term Lunar Capabilities

- In-situ manufacturing of complex parts and equipment
- Habitat and infrastructure construction (surface & subsurface)
- Life Support System – bio support (soil, fertilizers, etc.)
- Helium-3 isotope ($^3He$) mining

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# Lunar ISRU Commercialization

## A partnership between industry and NASA can benefit both parties

- NASA Benefits
  - Access to extensive terrestrial hardware and experience
  - A proactive stance from industry could steer technology development toward products that have near-term market potential
  - Support from non-aerospace industries will be critical to gaining the attention and support of Congress.
- Industry Benefits
  - Opportunities for cost savings include co-development of ISRU with a commercial partner to provide low-cost propellants for human exploration and other markets.
  - The technologies required to reliably generate products from space resources can lead to Earth & space industrial applications
  - Anchor tenant and co-funding for technology and operations into emerging markets (ex. In-space refueling)

## ISRU technologies with potential near-term Earth applications include:

- Miniaturized, low-power geologic sensors
- Wear-tolerant surfaces and bearings (increase component life)
- Electrostatic dust containment / removal
- Dry drilling systems
- Basalt processing into fibers, rebar, and other construction materials
- Micro-channel chemical and thermal processing systems

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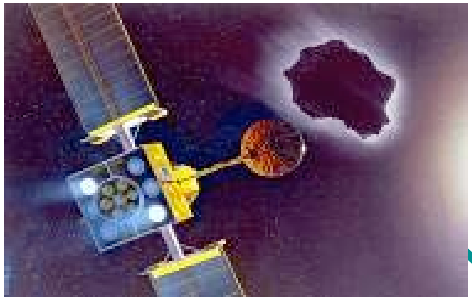
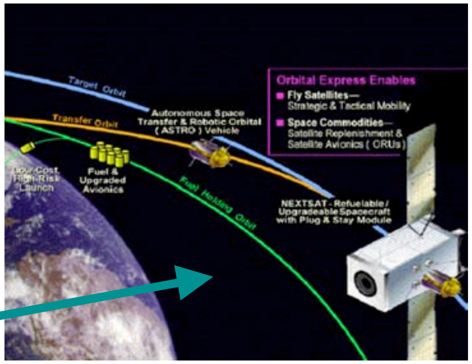
# Markets for Lunar Propellants & Materials at Earth-Moon L1 and Cis-Lunar Space






NASA-Science

Military Missions

Debris Management

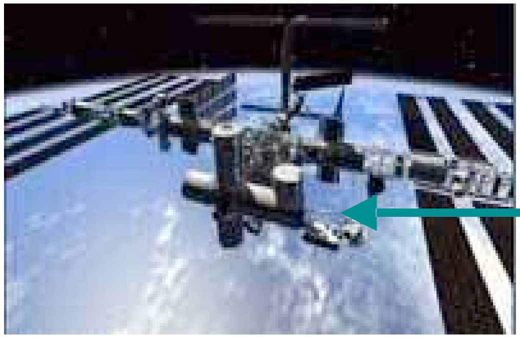
Satellite Servicing & Refueling

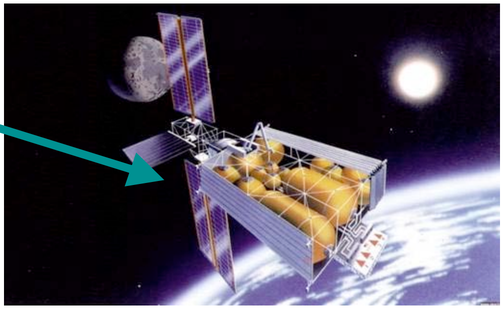
International Space Station

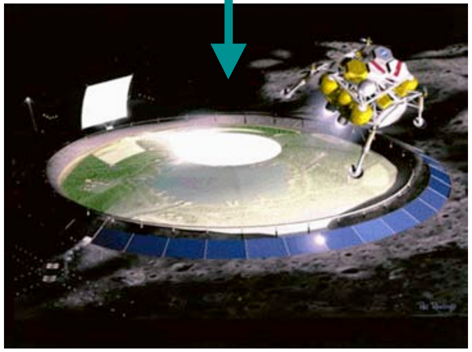
Human Exploration

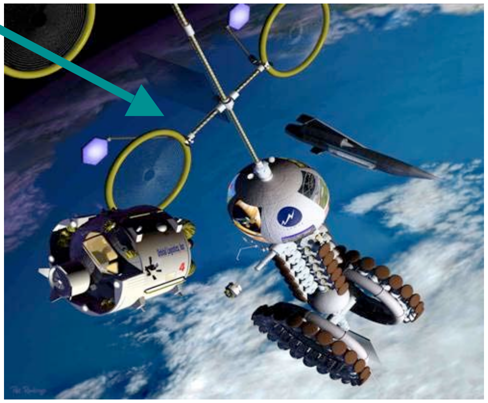
Space Solar Power

Self-Sustaining Colonies









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# Roadmap for Evolutionary ISRU Campaign

## Capabilities

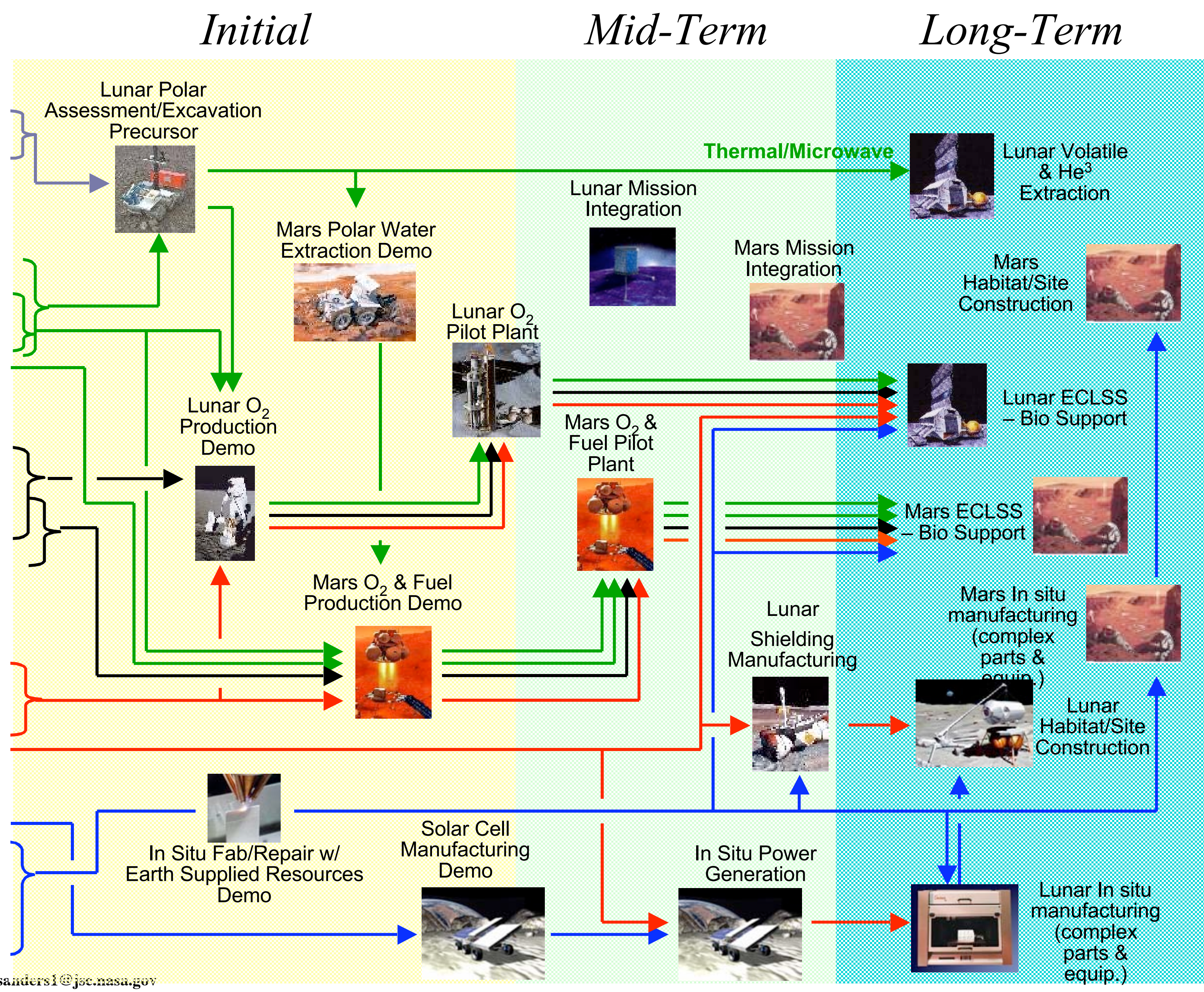
**Resource Assessment**
- Remote & Local Sensors
- Simulants

**In-Situ Resource Excavation & Separation**
- Regolith Excavation
- Thermal/Microwave Extraction
- $H_2O$ Separation
- $CO_2$ & $N_2$ Separation

**Resource Processing**
- Regolith Reduction for $O_2$ & Feedstock
- $CO_2$ Reduction
- $H_2O$ Reduction
- Fuel Production

**Consumable Storage & Distribution**
- Cryocoolers
- Light Weight Tanks
- Disconnects/pumps
- Transfer/Distribution

**In-Situ Manufacturing**
- Solar cell production
- Metallic part fab
- Polymer part fab.
- Ceramic part fab.
- Manufacturing NDE
- Metrology Processes

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# *Next Steps & Recommendations*

- Investigate Lunar resources, especially at lunar poles
- Incorporate & demonstrate ISRU hardware/systems in relevant environment in logical and orderly progression
- Maximize use of common technologies, hardware, and mission consumables between ISRU, propulsion, mobile power, life support, and EVA suit systems
- Evaluate & promote mission concepts and architectures that maximize use & benefits of ISRU
  - Robotic precursors and pre-positioning
  - Single base with surface traverse/hopping to maximize experience and infrastructure
  - Maximize Delta-V of lander/ascent vehicles with in-situ propellants
  - Reuse of transportation elements
  - Surface and in-space depots
  - Government-commercial partnerships

# BACKUP CHARTS

# ISRU Roadmap Capability Team

- Chair:  Gerald Sanders (JSC)
- Co-Chair:  Mike Duke (Colorado School of Mines)

- NASA
  - Lou Salerno (ARC)
  - Kurt Sacksteder (GRC)
  - Stu Nozette (HQ)
  - Don Rapp (JPL)
  - David McKay (JSC)
  - Kris Romig (JSC)
  - Robert Johnson (KSC)
  - William Larson (KSC)
  - Peter Curreri (MSFC)

- Industry
  - Ed McCullough (Boeing)
  - Eric Rice (Orbitec)
  - Larry Clark (Lockheed Martin)
  - Robert Zubrin (Pioneer Astronautics)

- Academia
  - Brad Blair (Colorado School of Mines)
  - Leslie Gertsch (Univ. of Missouri/Rolla)

# In-Situ Resource Utilization (ISRU)
## Capability Breakdown Structure

**In-Situ Resource Utilization 13.0**

Chair: Jerry Sanders/JSC
Co-Chair: Mike Duke (CSM)

- **Resource Extraction 13.1**
  Chair: Don Rapp/JPL, Leslie Gertsch/UMR
  - Resource Assessment 13.1.1
  - Resource Acquisition 13.1.2
  - Resource Separation/ Concentration 13.1.3
- **Resource & Waste Transportation 13.2**
  Chair: Kurt Sacksteder/GRC, Dale Boucher/NORCAT)
  - Fixed Mechanical Transportation 13.2.1
  - Mobile Mechanical Transportation 13.2.2
- **Resource Processing 13.3**
  Chair: Bill Larson/KSC, Larry Clark/LMA
  - Mission Consumable Production 13.3.1
  - Feedstock Production for In-Situ Manufacturing 13.3.2
  - Feedstock Production for Surface Construction 13.3.3
  - Feedstock Production for In-Situ Bio Support Systems 13.3.3
- **Surface Manufacturing with In-Situ Resources 13.4**
  Chair: Peter Curreri/MSFC, Ed McCullough/Boeing
  - Metallic Part Manufacturing 13.4.1
  - Polymer/Plastic Part Manufacturing 13.4.2
  - Ceramic Part Manufacturing 13.4.3
  - Locally Manufactured Energy Systems 13.4.4
  - Locally Integrated Systems & Components 13.4.5
  - Manufacturing Support Systems 13.4.6
- **Surface Construction 13.5**
  Chair: Kris Romig/JSC, Eric Rice/Orbitec
  - Surface Preparation 13.5.1
  - Excavation & Tunneling 13.5.2
  - Structure/Habitat Fabrication 13.5.3
  - Radiation & Plume Debris Shielding 13.5.4
  - Landing & Launch Site 13.5.5
- **Surface ISRU Product & Consumable Storage and Distribution 13.6**
  Chair: Robert Johnson/KSC, Bob Zubrin/Pioneer Ast.
  - Surface Cryogenic Fluid & Propellant Storage & Distribution 13.6.1
  - Processing Reagent Storage & Distribution 13.6.2
  - Gas Storage & Distribution 13.6.3
  - Utility Connections & Interfaces 13.6.4
  - Water storage & Distribution 13.6.5
  - Hazard Detection & Suppression 13.6.6

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# Commonality-Dependency of ISRU With Other Capability Roadmaps

| Capability Products To ISRU | | ISRU Products To Other Capabilities |
|---|---|---|
| • Solar & nuclear power to support power-intensive ISRU activities | High-Energy Power & Propulsion | • $H_2$ & $^3He$ for NTR & fusion; Ar for electric<br>• Solar array and collector manufacturing & assembly<br>• Rectenna fabrication for orbital power beaming<br>• Thermal storage material production & fabrication<br>• Radiation shields for nuclear reactors |
| • ISRU-compatible propulsion<br>• Delivery of ISRU capabilities to sites of exploration<br>• Electromagnetic launch systems for delivery of ISRU products | In-Space Transportation | • Propellant production and pressurant/purge gases for lander reuse and in-space depots<br>• Aeroshells from Regolith |
| | Advanced Telescopes & Observatories | • Shaping crater for collector<br>• In-situ construction and fabrication |
| • Resource location & characterization information<br>• Surface mobility system design & experience | Robotic Access to Planetary Surfaces | • Production of fuel cell reagents for rovers (vs solar arrays or RTGs for certain missions)<br>• Propellant production for surface hoppers or large sample return missions |
| • ISRU-compatible propulsion<br>• Delivery of ISRU capabilities to sites of exploration | Human Planetary Landing Systems | • Landing pads/plume debris shielding<br>• Propellant production/storage/transfer for lander reuse |
| • Carbon-based waste products as resource for ISRU | Human Health and Support Systems | • Habitat/shelter fabrication<br>• Gases for inflation & buffer gases<br>• Life support consumable production for backup<br>• Radiation shields from in-situ material<br>• Soil & bio-feedstock for plant growth<br>• Materials for in-situ manufacturing |
| • Crew/robotics/rovers to perform ISRU surface activities | Human Exploration Systems & Mobility | • Gases for science equipment<br>• Propellants & fuel cell reactants for surface vehicles and aero-bots<br>• $O_2$ production for EVA |
| • Robots/rovers to perform ISRU surface activities<br>• Software & FDIR logic for autonomous operation | Autonomous Systems & Robotics | |
| • Resource location & characterization information | Scientific Instruments & Sensors | |


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# Why Develop ISRU For Human Mars Exploration?

## Cost, Risk, and Benefit of human/robotic exploration are dependant upon:

- Mass delivered from Earth
- Surface operation and exploration effectiveness (No. of EVAs, crew size, science, etc.)
- Minimizing hazards and critical failures

## ISRU *Enables* lower mission mass & cost

- In-situ propellant production **reduces Earth launch mass** or number of launches required
  - 3.5:1 to 4:1 mass savings leverage from Moon/Mars surface back to Low Earth Orbit
- Life support consumable production can amount to **several tens of MT of savings**, depending on degree of recycling and functional redundancy; emergency cache
- In-situ production capabilities can reduce mission abort scenarios thereby reducing costs

## ISRU E*nables* "Flexible" & "Sustainable" planetary surface exploration

- In-situ production of oxygen ***enables*** **long-term surface EVA** (even with 100% closed loop life support)
- Use of common hardware & mission consumables enables increased flexibility
- In-situ fabrication of spare parts and surface infrastructure (power, habitats, shielding, etc.) enables sustainability and self-sufficiency
- ISRU can provide dissimilar redundancy thereby reducing mission risk

## Critical resources are available on Mars & possibly Moon

- Mars atmospheric resources, Lunar solar wind volatiles, and metal oxides and silicates are widely available
- Water on Mars may be widely available and water at lunar poles is possible
  - However form and location require further investigation

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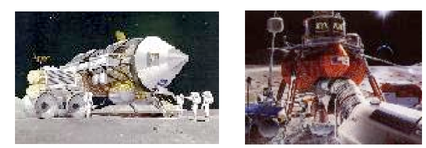
| ***Access to Surface Targets*** | Production and regeneration of propellants and fuel cell reagents enables transport rovers and robotic and human surface hoppers at a fraction of the cost compared to dedicated missions launched from Earth |
| ***Space Resource Utilization*** | All of above |

# ISRU Enables Sustainable & Affordable Transportation & Surface Exploration

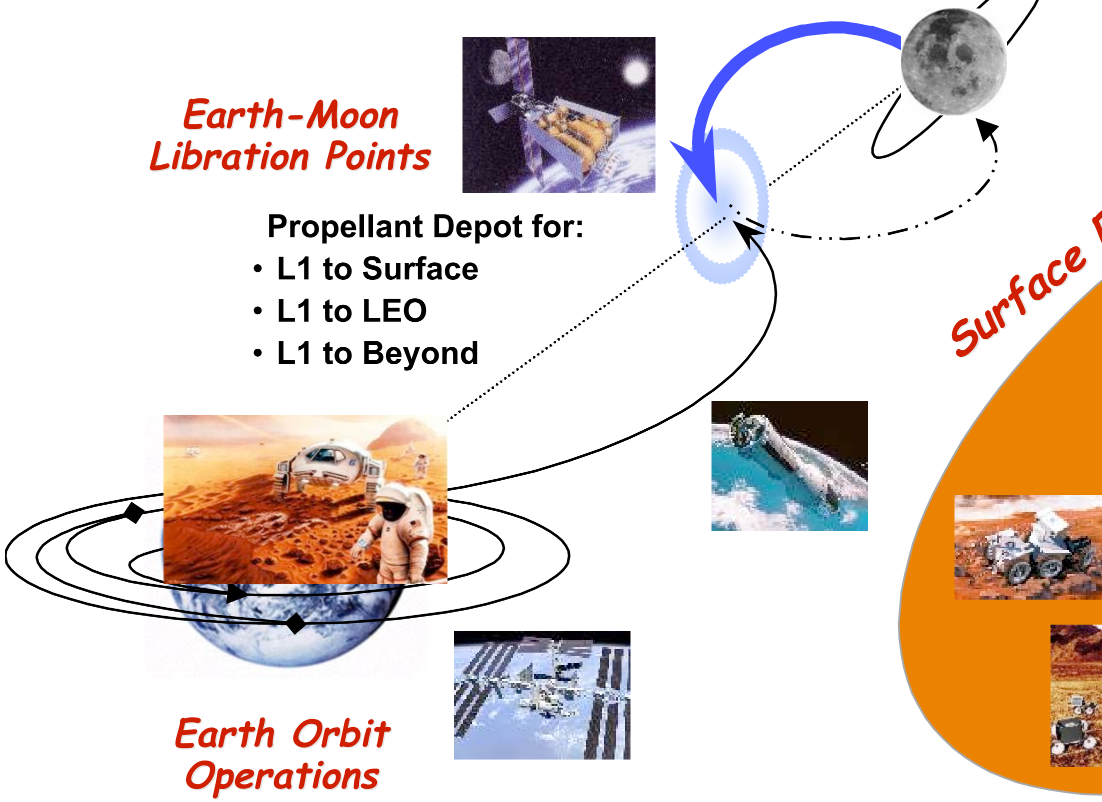
- Minimizes development & recurring mission cost due to common technologies and multiple applications
- Minimizes risk due to: functional backup for critical systems; flexibility in recovering from failures; placement & certification of Earth return vehicle and consumables prior to commitment to send humans
- Maximizes ability to reuse transportation assets
- Minimizes Earth launch mass & cost
- Enable ASARA

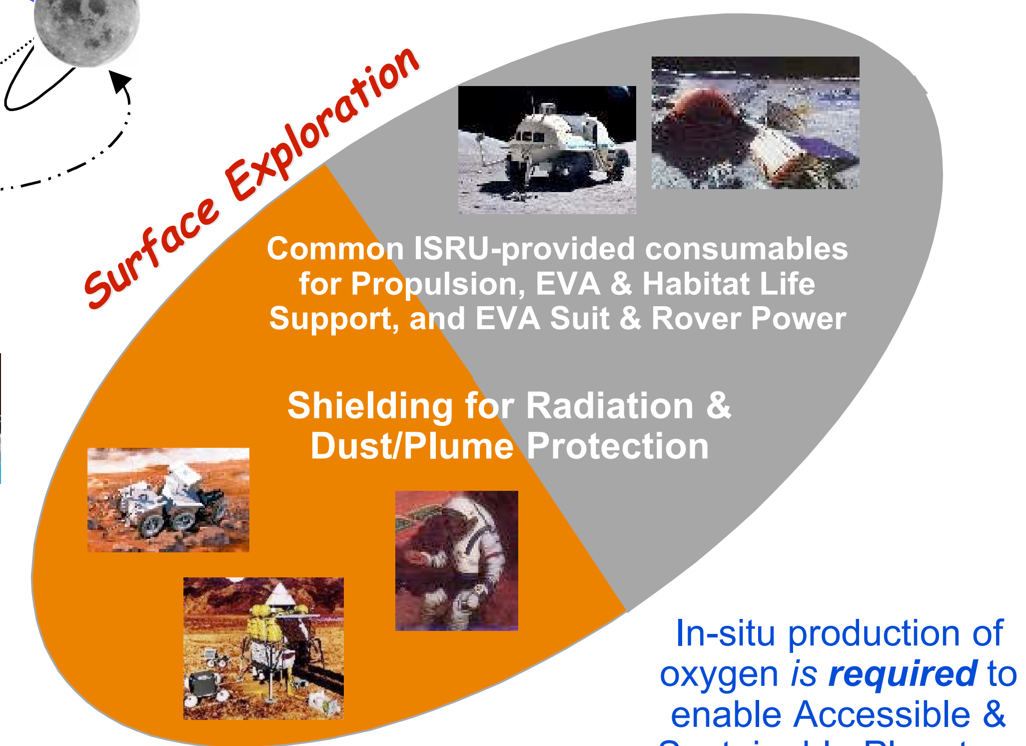
**Lander & Hopper Propellant Resupply & Servicing for Reuse**



*Lunar Surface*

**Oxygen, Water, & Propellant from Lunar ISRU**




In-situ production of oxygen *is* ***required*** to enable Accessible & Sustainable Planetary Surface exploration

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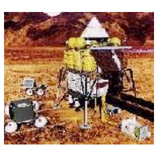
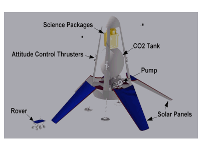
# *ISRU Enables Highly Capable, Affordable & Sustainable Surface Exploration Infrastructure*

**Robotic Precursors & Tele-robotic Science**


**EVA Astronaut w/ Robotic Assistant**


**EVA w/ Pressurized or Un-Pressurized Rovers**


**Crewed & Science Landers & Hoppers**


☑ ***Power-rich environment enables new science, capabilities, and relaxed power constraints***

- Single main power source produces oxygen & fuel cell reactants for all surface assets (EVA suits, rovers, etc.)
- High power on demand capability
- Swap new fuel cell reactants w/ used water on return with samples

☑ ***Modular common hardware for reduced logistics, higher reliability, and increased flexibility & safety***

- Reduced logistics needs
- Simplified spare parts manufacturing or scavenging possible

☑ ***Production of common mission consumables increases mission effectiveness, sustainability, & provides functional redundancy to minimize risk***

- Resupply EVA $O_2$ & FC reactants from Rover to extend EVA or in case of emergency

☑ ***Infrastructure is reusable and easily expandable from simple robotic lander to full human presence***

- More assets can be added with increase in production capability
- Increased surface access possible with ISRU
- ISRU hoppers enable surface access at fraction of cost of dedicated lander mission
- MAV size reduced if lander stage is reused with in-situ propellant

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# Common Resources & Processes Support Multiple Robotic/Human Mission Destinations

## *Planetary Resource Utilization is not Destination Specific!!*

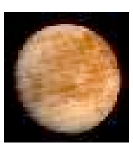
### Possible Destinations

Moon

Mars & Phobos

Near Earth Asteroids & Extinct Comets

Europa



Titan

### Common Resources

**Water**
- Moon
- Mars
- Comets
- Asteroids
- Europa
- Titan
- Triton
- ***Human Habitats***

**Carbon**
- Mars (atm)
- Asteroids
- Comets
- Titan
- ***Human Habitats***

**Metals & Oxides**
- Moon
- Mars
- Asteroids

**Helium-3**
- Moon
- Jupiter
- Saturn
- Uranus
- Neptune

### Core Building Blocks

- Atmosphere & Volatile Collection & Separation
- Regolith Processing to Extract $O_2$, Si, Metals
- In-Situ Manufacture of Parts & Solar Cells
- Water & Carbon Dioxide Processing
- Fine-grained Regolith Excavation & Refining
- Drilling
- Volatile Furnaces & Fluidized Beds
- 0-g & Surface Cryogenic Liquefaction, Storage, & Transfer

### Core Technologies

- Microchannel Adsorption
- Constituent Freezing
- Molecular Sieves

- Hydrogen/Carbo-thermal Reduction
- Acid Reduction

- Water Electrolysis
- $CO_2$ Electrolysis
- Sabatier Reactor
- RWGS Reactor
- Methane Reformer
- Microchannel Chem/thermal units

- Scoopers/buckets
- Conveyors/augers
- No fluid drilling

- Thermal/Microwave Heaters
- Heat Exchangers
- Liquid Vaporizers & Separators

- Cryo $O_2$ & Fuel Low Heatleak Tanks (0-g & reduced-g)
- Cryo $O_2$/Fuel Couplings & Transfer Lines

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# *Logical Schematic Diagram (LSD)*
# ***Space Resource Utilization***

## Technology Needs

- Low mass, low power in-situ water detector
- Depth Profiling/mineralogy

- Microchannel chemical/thermal components & systems
- Carbon dioxide and Water dissociation
- Conversion & energy efficient fuel/hydrocarbon reactors
- Efficient gas/liquid separation
- Efficient gas/gas separation

- High temperature/molten furnaces/crucibles
- Long-life non-reacting electrodes
- Efficient thermal energy generation & transfer
- Low/0-leakage regolith inlet/waste outlet devices

- Excavation of loosely bound regolith in top few meter
- Non-lubricated drills
- Microgravity physical/electro separation

- High capacity liquefaction (10's kW)
- Dust occluding disconnects
- Low mass/high volume storage tanks
- Low heat leak valves etc
- Low loss Cryo transfer

## Sub System Concepts

- Autonomous Control/FDIR

- Prospecting & Resource Characterization

- Regolith Processing to Extract volatiles (water, solar wind, etc.)
- Regolith Processing to Extract Oxygen
- Atmosphere & Volatile Collection & Separation
- Water & Carbon Dioxide Processing
- Bio-system support processing (soil, fertilizer, etc.)
- Bio-waste processing

- Raw materials extraction (Si, Fe, TiO2, Al, etc.)
- Processing of extracted resources into glasses, fibers, ceramics, etc.
- Machining, part forming, & NDE
- In-Situ Manufacture of Solar Cells, power transmit ion

- Fine-grained regolith excavation & refining
- Drilling
- Transport & placement
- Separation and beneficiation
- Construction & assembly equipment

- Surface Cryogenic Liquefaction, Storage, & Transfer

## System Concepts

**Consumables Production**
- Propellant
- Life Support
- Power
- Science
- Feedstock

**Manufacturing**
- Spare Parts
- Integrated Products
- Const mat'ls (bricks, beams, etc.)

**Construction**
- Shielding
- Habitats/ structures
- Landing pads & roads

**Power & Utilities**
- Solar arrays
- Thermal storage
- Depots

## Capability

Design Challenges

Wide temp range

Micro/low g ops

Vacuum/low pressure atm

Launch mass/volume

No/low maintenance

Autonomy

Abrasive Regolith

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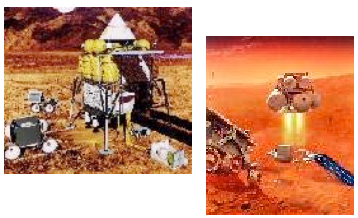
# *Core ISRU Technologies Enable Multiple Applications*

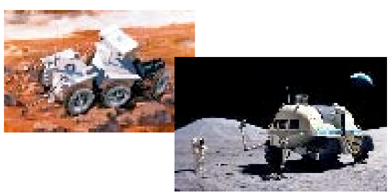
## *Planetary Resource Utilization Maximizes Benefits, Flexibility, & Affordability*

- Modular hardware & common mission fluids reduced logistics, increases reliability & flexibility, and reduces development and mission costs

**In-Situ Production Of Consumables for Propulsion, Power, & ECLSS**



**Fuel Cell Power for Spacecraft, Rovers & EVA**



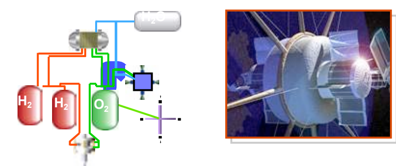
**0-g & Reduced-g Propellant Transfer**

### *Core Technologies*

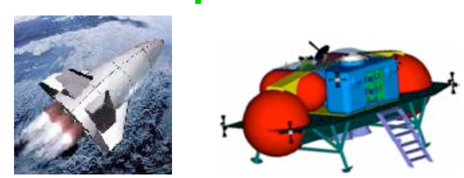
- $CO_2$ & $N_2$ Acquisition & Separation
- Sabatier Reactor
- RWGS Reactor
- $CO_2$ Electrolysis
- Methane Reforming
- $H_2O$ Separators
- $H_2O$ Electrolysis
- $H_2O$ Storage
- Heat Exchangers
- Liquid Vaporizers
- $O_2$ & Fuel Storage (0-g & reduced-g)
- $O_2$ Feed & Transfer Lines
- $O_2$/Fuel Couplings
- Fuel Cells
- $O_2$/Fuel Igniters & Thrusters

**Life Support Systems for Habitats & EVA**

**Water – Gaseous $H_2$/$O_2$ Based Propulsion**



**Non-Toxic $O_2$-Based Propulsion**



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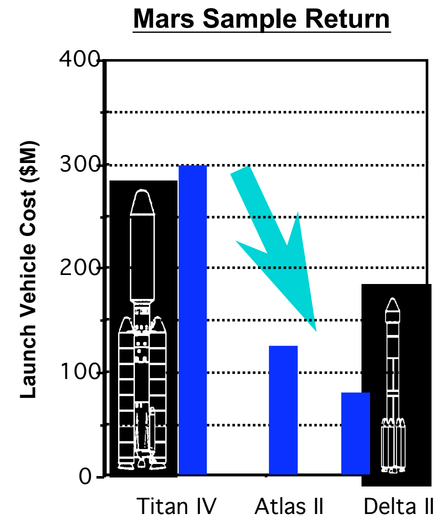
# ISRU vs. Non-ISRU Mars Mission Study Results

## Mars Sample Return with & without ISRU (Multiple Studies)

- **20% to 35% reduction** in launch **mass** for Mars Sample Return
- Possible use of Delta II or Atlas II versus Titan IV or Proton **reduces launch cost** by a **factor of 2 to 3**
- ISRU ***enables*** Direct Earth return sample return mission with large sample (5+ kg)
- Propellant production unit for Mars sample return mission is:
  - Same scale of production unit to supply EVA oxygen or EVA fuel cell powered rover
  - Scalable to human mission propellant production package




## Human Mars Missions

- **21 to 25% mass reduction** for Human Mars Design Reference Mission
  - Smaller lander = smaller Mars trans stage and Mars orbit capture vehicles
  - Greater mass savings with increasing Delta-V (i.e. higher Mars rendezvous orbit)
- **3.63:1 mass savings leverage** from Mars surface back to Low Earth Orbit, i.e. 30 MT of in-situ propellant production equals >100 MT in Low Earth Orbit

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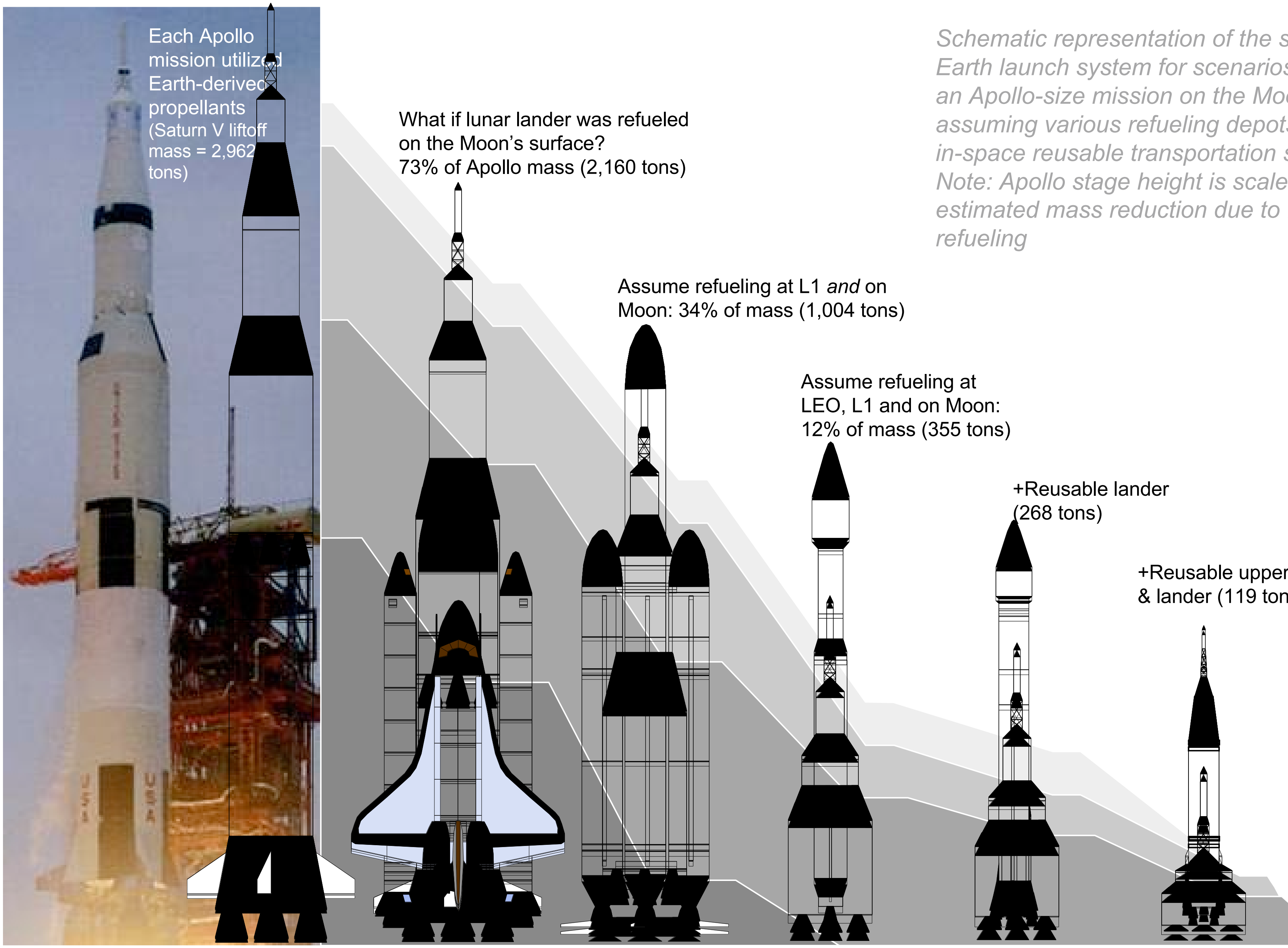
# CSM Study: Propellant from the Moon will revolutionize our current space transportation approach

*Schematic representation of the scale of an Earth launch system for scenarios to land an Apollo-size mission on the Moon, assuming various refueling depots and an in-space reusable transportation system. Note: Apollo stage height is scaled by estimated mass reduction due to ISRU refueling*



# Lunar Resources Processing Options

## LUNAR RESOURCES

### MARE REGOLITH

Ilmenite - 15%

| | |
|---|---|
| $FeO \cdot TiO_2$ | 98.5% |

Pyroxene - 50%

| | |
|---|---|
| $CaO \cdot SiO_2$ | 36.7% |
| $MgO \cdot SiO_2$ | 29.2% |
| $FeO \cdot SiO_2$ | 17.6% |
| $Al_2O_3 \cdot SiO_2$ | 9.6% |
| $TiO_2 \cdot SiO_2$ | 6.9% |

Olivine - 15%

| | |
|---|---|
| $2MgO \cdot SiO_2$ | 56.6% |
| $2FeO \cdot SiO_2$ | 42.7% |

Anorthite - 20%

| | |
|---|---|
| $CaO \cdot Al_2O_3 \cdot SiO_2$ | 97.7% |

### VOLATILES (Solar Wind & Polar Ice/$H_2$)

| | |
|---|---|
| Hydrogen ($H_2$) | 50 - 150 ppm |
| Helium (He) | 3 - 50 ppm |
| Helium-3 ($^3He$) | $10^{-2}$ ppm |
| Carbon (C) | 100 - 150 ppm |
| Polar Water ($H_2O$)/$H_2$ | 1 - 10% |

→ Thermal Volatile Extraction

### Hydrogen Reduction of Ilmenite/glass Process

Fluidized Bed Reactor

$2FeTiO_3 + 2H_2 \xrightarrow{900^\circ C} 2H_2O + 2Fe +$ → 2Fe

Water electrolysis

$O_2 + 2H_2 \xleftarrow{25^\circ C} 2H_2O$ → $O_2$

### Sulfuric Acid Reduction Process

Desolve/Digest Reactor

$2FeTiO_3 + 2H_2SO_4 \rightarrow 2H_2O + 2FeSO_4 +$

Electrolysis bed

$O_2 + 2Fe + 2H_2SO_4 \leftarrow 2H_2O + 2FeSO_4$ → $O_2$, 2Fe

### Methane Reduction (Carbothermal) Process

Methane Reduction Furnace

$2FeTiO_3$, $Fe_2SiO_4$, $FeSiO_3$, $Mg_2SiO_4$, $MgSiO$, $CaSiO_3$ + $2CH_4 \xrightarrow{1625^\circ C} 2CO + 4H_2 +$

- $2TiO_2 + 2Fe$ → 2Fe
- $2FeO + Si$
- $FeO + Si$
- $2MgO + Si$
- $MgO + Si$
- $CaO + Si$

→ Si

Methane Reformer

$2H_2O + 2CH_4 \xleftarrow{250^\circ C} 2CO + 6H_2$

Water electrolysis

$2H_2O \xrightarrow{25^\circ C} 2H_2 + O_2$ → $O_2$

### Molten Electrolysis

Molten Electrolysis Reactor

- $2SiO_2 \rightarrow 2SiO + O_2$ → $O_2$
- $2FeTiO_3 \rightarrow 2Fe + 2TiO_2 + O_2$
- $2FeO \rightarrow 2Fe + O_2$

→ $O_2$, 2Fe

### Vapor Pyrolysis Process

Pyrolysis Reactor/Condenser

- $2SiO_2 \xrightarrow{>2000^\circ C} 2SiO + O_2$ → $O_2$
- $2FeTiO_3 \xrightarrow{2500^\circ C} 2Fe + 2TiO_2 + O_2$
- $2FeO \xrightarrow{>2000^\circ C} 2Fe + O_2$ → $O_2$, 2Fe
- $2Al_2O_3 \xrightarrow{>2000^\circ C} 4AlO + O_2$ → $O_2$
- $2Al_2O_3 \xrightarrow{>2000^\circ C} 2AlO + 2Al + O_2$ → $O_2$, 2Al
- $2MgO \xrightarrow{>2000^\circ C} 2Mg + O_2$
- $2CaO \xrightarrow{>2000^\circ C} 2Ca + O_2$ → $O_2$
- $2CaAl_2Si_2O_8 \xrightarrow{2500^\circ C} 2Ca + 4AlO + 4SiO + 4O_2$ → $4O_2$, 2Ca
- $2CaAl_2Si_2O_8 \xrightarrow{2500^\circ C} 2Ca + 2AlO + 2Al + 4SiO + 5O_2$ → $5O_2$, 2Al, 2Ca

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# *Past & Current Mars ISRU Activities*

## ISRU Technology Development

- Mars atmosphere adsorption pump collection (JPL, ARC, LMA, JSC, PNNL)
- Mars atmosphere solidification pump collection (LMA, SBIR)
- Volatile extraction from lunar soil (JSC/CSM)
- Zirconia $CO_2$ Electrolysis (Univ. of Arizona, Allied Signal, Old Dominion, SBIR)
- Water Electrolysis/Decomposition (JSC, LMA, SBIR)
- Reverse Water Gas Shift (SBIRs, KSC)
- Methane reformer (JPL, SBIR)
- Hydrocarbon fuel development (SBIR, JSC)
- Microchannel Chemical/Thermal System Technology for ISRU (PNNL, SBIR)
- Surface cryogenic liquefaction and storage (JSC, NIST, SBIRs, LMA)

## ISRU Subsystem & System Development & Ground Testing

- $CO_2$ collection and storage subsystems tested
- 1$^{st}$ Generation Sabatier/Water Electrolysis (SWE) breadboard under ambient & Mars environment testing
- 1$^{st}$ Generation Reverse Water Gas Shift with and w/o Fuel production
- 2$^{nd}$ Gen SWE system breadboard - designed and subsystems built

## ISRU Flight Demonstrations

- Mars ISPP Precursor (MIP) flight demo manifested on 2001Mars Surveyor Lander
  - Flight hardware certified and placed in Bonded Storage at JSC

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# Past & Current Lunar ISRU Activities

## ISRU Technology Development

- Lunar polar regolith excavation (CSM/LMA)
- Hydrogen reduction of ilmenite/pyroclastic glass (JSC, Carbotek, Univ of Tenn.)
- Carbothermal reduction of regolith (Aeroject/ISP, Orbitec)

## ISRU Subsystem & System Development & Ground Testing

- Hydrogen reduction of ilmenite/pyroclastic glass (JSC, Carbotek, Univ of Tenn.)
- Carbothermal reduction of regolith (Aeroject/ISP, Orbitec)

## ISRU Flight Demonstrations

- RESOLVE:

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# *ISRU Challenges*

Maximize benefit of using resources, in the shortest amount of time, while minimizing crew involvement and Earth delivered infrastructure

- **Early Mass, Cost, and/or Risk Reduction Benefits**
  - Processing and manufacturing techniques capable of producing 100's to 1000's their own mass of product in their useful lifetimes, with reasonable quality.
  - Construction and erection techniques capable of producing complex structures from a variety of available materials.
  - In-situ manufacture of spare parts and equipment with the minimum of required equipment and crew training
  - Methods for energy efficient extracting oxygen and other consumables from lunar or Mars regolith
  - Methods for mass, power, and volume efficient delivery and storage of hydrogen

- **Long-duration, autonomous operation**
  - Autonomous control & failure recovery (No crew for maintenance; Non-continuous monitoring)
  - Long-duration operation (ex. 500 days on Mars surface for propellant production)

- **High reliability and minimum (zero) maintenance**
  - High reliability due to no (or minimal) maintenance capability for pre-deployed and robotic mission applications
  - Networking/processing strategies (idle redundancy vs over-production/degraded performance)
  - Development of highly reliable thermal/mechanical cycle units (valves, pumps, heat exchangers, etc.)
  - Development of highly reliable, autonomous calibration control hardware (sensors, flowmeters, etc.)

# ISRU Challenges (Cont.)

- **Operation in severe environments**
  - Efficient excavation of resources in extremely cold (ex. Lunar permanent shadows), dusty/abrasive, and/or micro-g environments (Asteroids, comets, Mars moons, etc.)
  - Methods to mitigate dust/filtration for Mars atmospheric processing

- **Resource Unknowns**
  - Is water/ice, hydrogen, or both located in lunar polar and permanently shadowed crater? Is the ice/hydrogen accessible/useable?
  - How much water is in the Mars regolith and can it be efficiently extracted? Is subterranean water present, what form is it in, and where?
  - What are the material chemical and physical properties of Phobos & NEO asteroids? How much water is available and in what form/concentration is it found (ice, hydrated clays, …)?

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# *Why Fly ISRU Flight Demonstrations?*

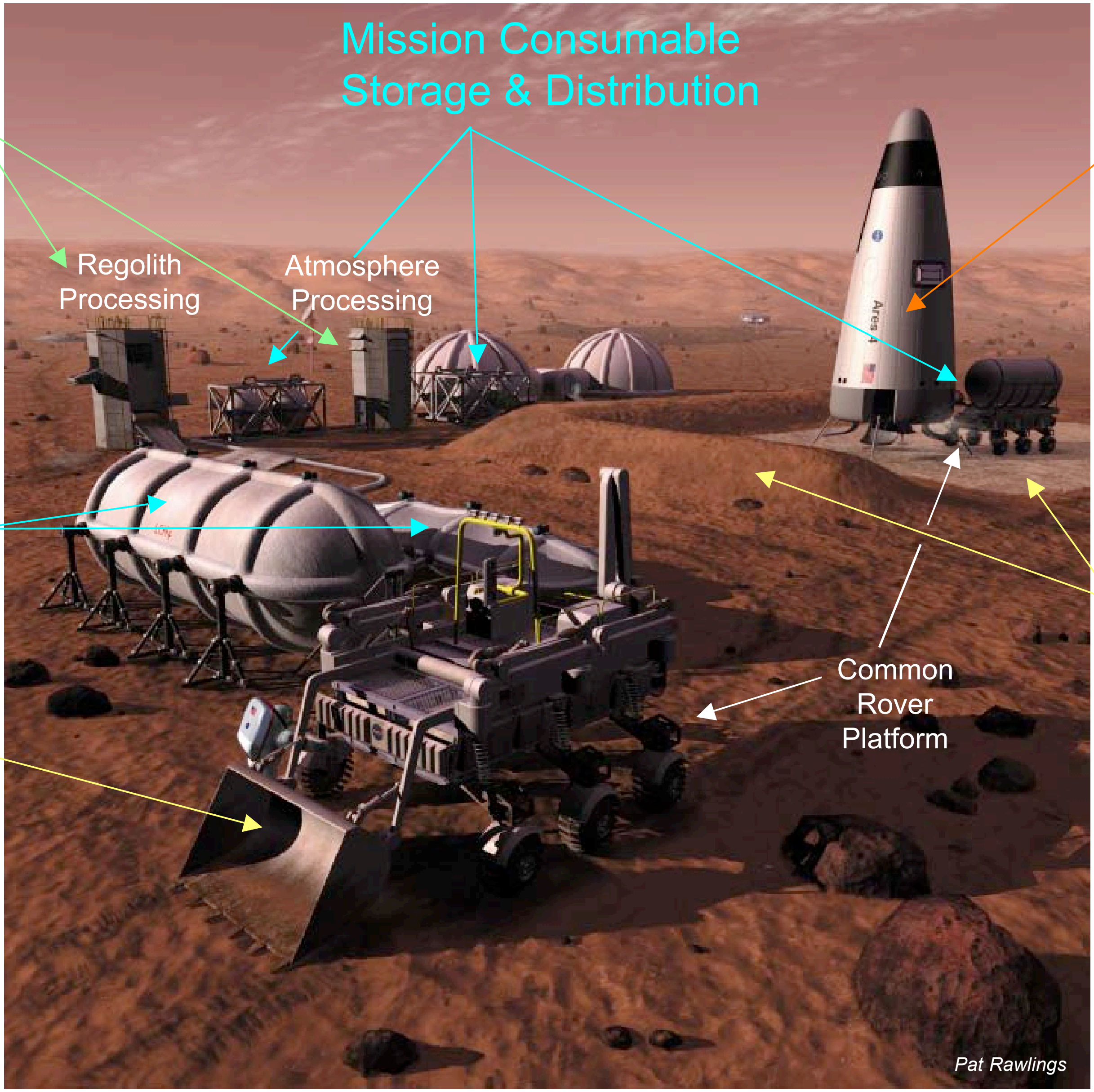
- Validate Earth-based development & testing
  - Mars environment interaction with ISRU plant can't be fully simulated on Earth
  - Extended periods of test to simulate long duration flights will be difficult to perform
- Utilize Flight Demonstrations to increase confidence in ISRU
  - Utilize opportunities to demonstrate ISRU technologies in non-critical path situations
  - Fly progressively more complex ISRU demonstration missions to minimize the risk and increase the confidence in use of ISRU for Mars sample return and human missions
- Reduce mission cost & design envelope
  - Incorporation of ISRU into robotic sample return missions will enable larger samples to be returned
  - Incorporation of ISRU into human missions will enable smaller landers or reduced launch vehicle needs
  - ISRU can provide $O_2$ for EVA and pressurized rovers, and will provide functional backups to ECLSS $O_2$ and $H_2O$ sources.
- Engage & Excite Public
  - ISRU supports the American pioneer spirit of exploration by "living off the land"
  - It shows the public NASA is serious about Human exploration of Mars for a fraction of the cost of a full up human mission. Demonstrations build public support and constituency for eventual human exploration

# Example Mars Base With ISRU Capability

Resource Processing Plants

Collapsible/ Inflatable Cryogenic Tanks

Multi-use Construction/ Excavator: resources, berms, nuclear power plant placement, etc.




Reusable lander/ascent vehicle or surface hopper fueled with in-situ propellants

Landing pad & plume exhaust berm

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